

An energy and exergy analysis of a high-efficiency engine trigeneration system for a hospital: A case study methodology based on annual energy demand profiles



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ABSTRACT

The efficient use of natural resources is an important contribution to the creation of a more sustainable world. Decentralized electricity production through trigeneration systems can save primary energy if these systems operate with a high energy utilization factor (EUF). A high EUF is obtained when the system produces electricity and a substantial amount of the energy rejected by the prime mover is used to meet on-site thermal demands. Energy consumption in buildings varies as the activity, climate and occupancy change at different hours of the day, days of the week, weather conditions and seasons. In this study an annual analysis of an engine trigeneration system is developed as an integrated thermal system (ITS) through a computational simulation program. The ITS simulation uses the characteristics of the system, characteristics of the individual pieces of equipment, design assumptions and parameters, off-design operating conditions, energy demands profiles of the site and climatic data to evaluate the system performance. The obtained results revealed an EUF between 58 and 77% and an exergy efficiency between 35 and 41% for the system. The primary energy savings (PES) analysis showed that the proposed trigeneration system is better than the best available technology used in centralized thermal plants.

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1. Introduction

Sustainably using natural resources is an important contribution to reducing the environmental impact of human activities. Climate change is expected to be extended by increasing concentrations of greenhouse gases produced by human activities, such as burning fossil fuels and deforestation. Water vapor, carbon dioxide (CO₂), methane and ozone are the main greenhouse gases. Electricity production is a major cause of the current high levels of CO₂ emissions, given that fossil fuels represented 67.4% of the global electricity produced in 2010 [1]. CO₂ annual emission rose more than 93% between 1973 and 2010, annual emissions were 15,637 Mt (million tons) in 1973 and 30,326 Mt in 2010 [1]. High-efficiency electricity production systems that use fossil fuels can reduce the rise in CO₂ emissions, assist in expanding electrical systems (due to increasing electricity demands in the world) and substitute for existing low-efficiency thermal plants. Thermal plant efficiencies are being raised by advances in engineering fields, such as materials, manufacturing process, fluid flow, heat transfer, combustion,

instrumentation, electronics and others. A trigeneration system takes advantage of these engineering advances and incorporates them into the equipment, however, high-efficiency trigeneration systems need a good match between the site energy load and the trigeneration system energy.

A previous study [2] that simulated a gas engine trigeneration system, and summer energy demands, which utilized the primary energy savings (PES) analysis, concluded that the trigeneration system can compete with the best available technology in centralized thermal plants (thermal efficiency close to 60%) if a substantial amount of the prime mover rejected energy is recovered to meet site energy demands. PES analysis can be utilized to compare the performance of trigeneration system and centralized thermal plant using system components efficiencies, site to source energy conversion factors, and different energy demand scenarios [3,4].

Trigeneration systems, or combined heat, cooling and power systems, can be applied in industrial processes and buildings. Industrial processes and administrative buildings can be located at the same site and their associated energy demands can be met by a trigeneration system. Trigeneration is proposed to participate in an integrated multi-energy systems (MES) framework, whereby electricity, heat, cooling, fuels, transport, and so on optimally interact with each other [5].

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Nomenclature

$\dot{E}_{\text{steam}}$	energy rate of produced steam (kW)
$\dot{E}_{\text{ht}}$	energy rate of produced hot water (kW)
$\dot{E}_{\text{cw}}$	energy rate of produced chilled water (kW)
EUF	energy utilization factor
$\dot{E}x_{\text{flow}}$	exergy rate of trigeneration flow products (kW)
$\dot{E}x_{\text{steam}}$	exergy rate of produced steam flow (kW)
$\dot{E}x_{\text{ht}}$	exergy rate of produced hot water flow (kW)
$\dot{E}x_{\text{cw}}$	exergy rate of produced chilled water flow (kW)
h	specific enthalpy (kJ/kg)
LHV_{fuel}	fuel lower heating value (kJ/kg)
ech_{fuel}	fuel chemical exergy (kJ/kg)
$\dot{m}_{\text{cog}}$	mass flow rate of trigeneration products (kg/s)
$\dot{m}_{\text{fuel}}$	fuel mass flow rate (kg/s)
s	specific entropy (kJ/kg.K)
T_0	ambient reference temperature (K)
$\dot{W}_{\text{net}}$	net electrical power (kW)
ε	exergy efficiency of the trigeneration system

The prime mover (power production unit) is the main equipment of trigeneration systems. Different prime movers can be utilized, including (i) internal combustion engines [6–8], (ii) gas turbines [9] and micro gas turbines [10–12], (iii) fuel cells [13,14], (iv) steam turbines and (v) stirling engines [15]. A combination of different prime movers in the same system can also be utilized [16].

Energy and exergy analysis are used to compare the performance of different systems. Design parameters can be modified to raise the efficiency. The global and local environmental impact of natural gas trigeneration systems is a concern when evaluating decentralized electricity production. CO₂ emissions are associated with the system efficiency, while NO_x and CO depend on the prime mover type. Studies evaluating the exhaust gas emissions of cogeneration and trigeneration systems [17–20] can contribute to the decision. Biofuels can also be applied, Huang et al. [21] presented a study evaluating the performance of a building engine trigeneration system fueled by biogas. A biogas fueled micro gas turbine cogeneration system for a sewage treatment plant was investigated by Basrawi et al. [12].

Computer-based decision support tools are being developed for the evaluation of thermal plant performance [22,23], as this analysis requires several types of operational data, flows and thermodynamic properties. Computational simulations can contribute to predicting performance and finding high-efficiency solutions.

The objective of this study is to demonstrate a methodology, applied as a case study, to predict the performance of an engine trigeneration system. This methodology is proposed as a tool to develop high-efficiency solutions. The software COGMCI [24] is utilized to develop the simulation analysis. The flexibility of this software in computational simulation enables system performance prediction for different configurations, capacities (sizes) and operation modes, e.g., designs for matching base-loads or for exporting surplus. The computational program simulates the system as an integrated thermal system (ITS), and provides an analysis of the hourly profile of a given trigeneration system producing electricity and thermal flows (steam, hot water, chilled water). Simulation outside the design condition (i.e., partial engine load) has shown that engine load affects the energy delivered to the heat exchangers for hot water production, the energy delivered to the absorption chiller for chilled water production, and the energy delivered to the heat recovery steam generator (HRSG) for steam production. Annual site energy demand profiles are compared with the trigeneration system energy by means of equipment simulation methods.

Three criteria are used to evaluate the system performance: (i) EUF, (ii) exergy efficiency and (iii) PES.

2. Case study: hospital

The energy demand of a Brazilian university hospital is assessed. The hospital, classified as a medium hospital [25], is located in the southeastern region of Brazil and has a constructed area of 65,000 m² (403 beds, an intensive care unit for 50 persons and 25 surgery rooms). The hospital buys electricity from the grid; the hospital also produces steam in a combustible oil-fueled steam generator, hot water in oil-fueled boilers and chilled water in a water-cooled screw compressor chiller.

Energy consumption in buildings varies as the activity, climate and occupancy changes at the different hours of the day, days of the week, weather conditions and seasons. Several authors have studied energy consumption in buildings. Ortega et al. [26] presented a method for the selection of typical days for the characterization of energy demand in buildings. EnergyPlus [27] benchmark models were proposed to estimate energy consumption in buildings by Fumo et al. [28]. In accordance with Cardona and Piacentino [6] “a suitable examination period can be considered equal to one year, the minimum time after which consumption should theoretically, repeat themselves approximately equal”.

In this study, the energy demand profiles were obtained through a data acquisition system installed to register the hospital energy demands (Fig. 1). The system monitored the total electricity demand, sanitary hot water demand, steam demand and electricity demand from the electrical chillers at a one-hour time interval. The daily weather profiles were obtained at a climatic monitoring station located at the university campus. The data were obtained in 2006.

The mean daily energy demand profiles were grouped for eight different groups with similar behavior: (i) summer weekdays (60 days), (ii) summer weekends/holidays (29 days), (iii) autumn weekdays (65 days), (iv) autumn weekends/holidays (28 days), (v) winter weekdays (67 days), (vi) winter weekends/holidays (27 days), (vii) spring weekdays (60 days) and (viii) spring weekends/holidays (29 days). The climatic data were grouped in mean daily profiles for each weather season.

Fig. 2a and b shows the mean electricity demand profiles. Fig. 3a and b show the mean sanitary hot water demand profile. Fig. 4a and b show the steam demand profile. Fig. 5 shows the electrical chillers demand profile (cooling load) in refrigeration tons (RT, 1 RT = 3.52 kW); the electricity demand of the chiller is included in the electricity demand profiles (Fig. 2a and b). Fig. 6 shows the mean dry bulb temperature and relative humidity season profiles.

In Table 1, the daily electricity, hot water, steam and chilled water consumptions of the hospital were calculated taking into account the mean demand profiles. Table 2 reveals the daily and

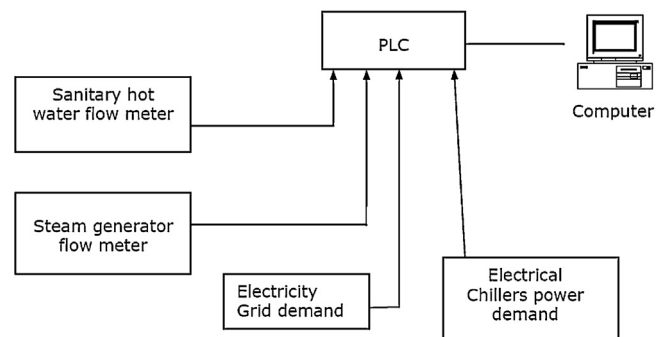
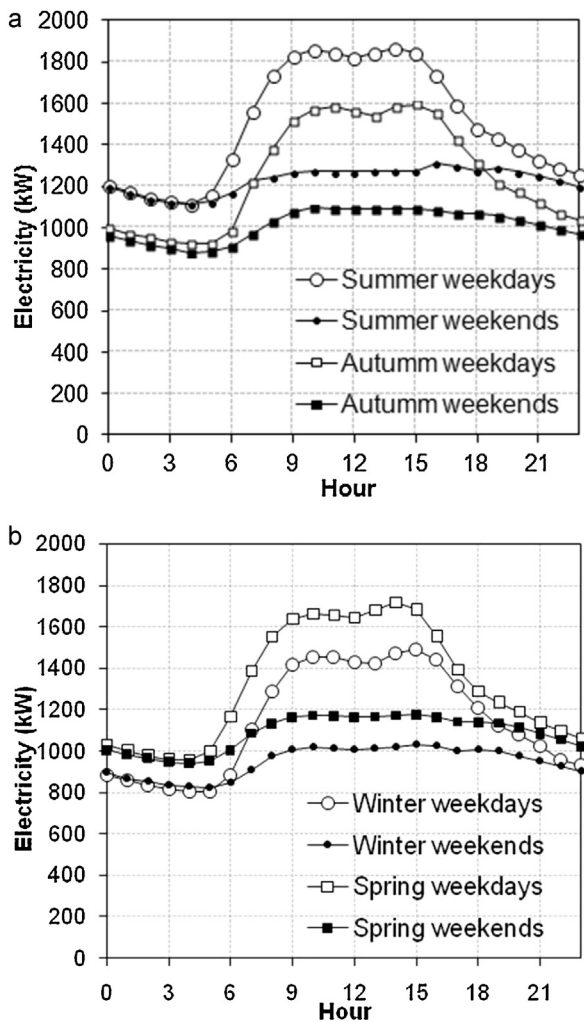


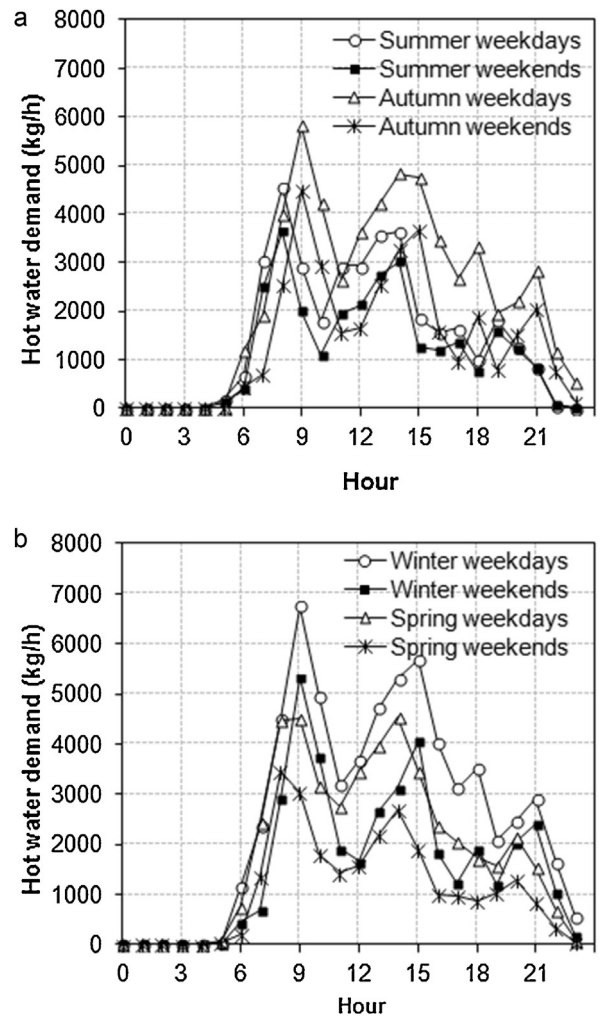
Fig. 1. Data acquisition system.

Table 1
Daily utilities consumption.

	Summer		Autumn		Winter		Spring	
	Weekdays	Weekends	Weekdays	Weekends	Weekdays	Weekends	Weekdays	Weekends
Electricity (kWh/day)	35973	29542	30126	24320	27521	22776	31682	26113
Steam (kg/day)	24172	22348	16340	17580	14852	18408	17432	20224
Hot water (m ³ /day)	36.3	28.0	55.5	33.7	62.7	38.5	45.9	26.1
Chilled water (RT/day)	5351	4811	3536	3377	2454	2309	4299	3845

**Fig. 2.** Hospital electricity demand (kW): (a) summer and autumn; (b) winter and spring.

annual energy consumption of the hospital. The electricity consumption of the electrical chiller is included in the daily electricity consumption line (line 1). The energy rate of the steam and hot water were calculated as the mass flow rate multiplied by the enthalpy differences. Sanitary hot water is warmed from 22.2 to

**Fig. 3.** Hospital hot water demand (kg/h): (a) summer and autumn; (b) winter and spring.

50 °C and the saturated steam production (8 bar) assumes that water enters at 70 °C. Assuming that steam and hot water are produced with an efficiency of 80% and electricity is produced with an efficiency of 38%, the daily primary energy consumption was calculated (line 4 of Table 2). Multiplying the daily primary energy

Table 2
Daily and annual energy consumption (without trigeneration).

Without Trigeneration	Summer		Autumn		Winter		Spring	
	Weekdays	Weekends	Weekdays	Weekends	Weekdays	Weekends	Weekdays	Weekends
Electricity consumption (kWh/day)	35973.0	29542.0	30126.0	24320.0	27521.0	22776.0	31682.0	26113.0
Steam consumption (kWh/day)	16609.3	15356.0	11227.7	12079.7	10205.2	12648.7	11978.0	13896.5
Hot water consumption (kWh/day)	1174.3	903.5	1791.7	1088.0	2024.5	1244.2	1483.4	844.0
Daily energy consumption (kWh/day)	116895.2	98066.4	95553.2	80459.7	87710.9	77302.9	100200.5	87144.0
annual consumption (kWh/year)	7013714.6	2843926.2	6210957.7	2252871.4	5876628.1	2087177.8	6012027.3	2527176.8
Annual total consumption (kWh/year)	34824479.92							

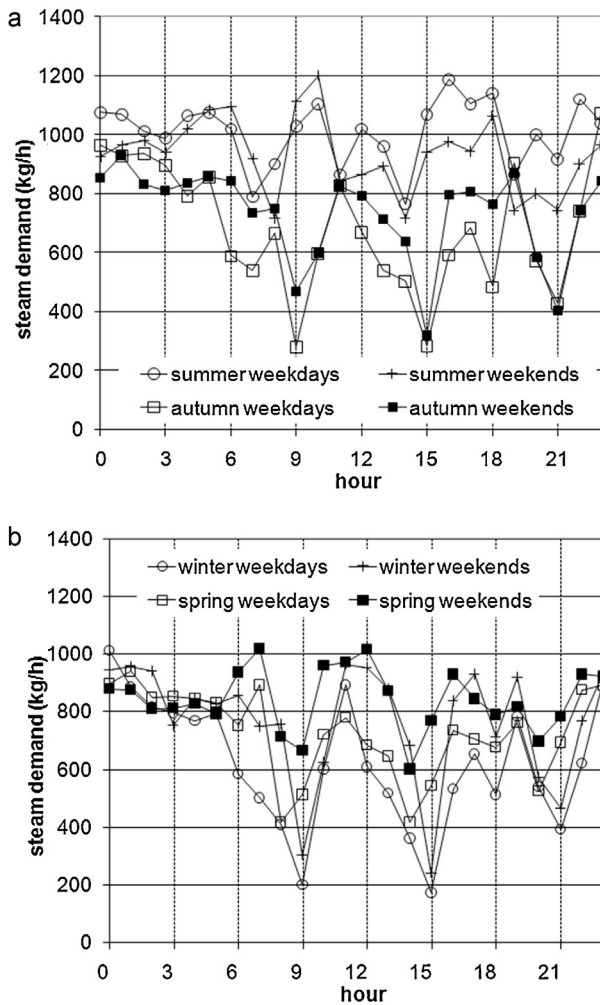


Fig. 4. Hospital steam demand (kg/h): (a) summer and autumn; (b) winter and spring.

consumption by the number of days in each group, the primary energy consumption for each group was calculated (line 5). The sum of the group energy consumption is the annual primary energy consumption, calculated as 34,824,480 kWh/year (last line of Table 2).

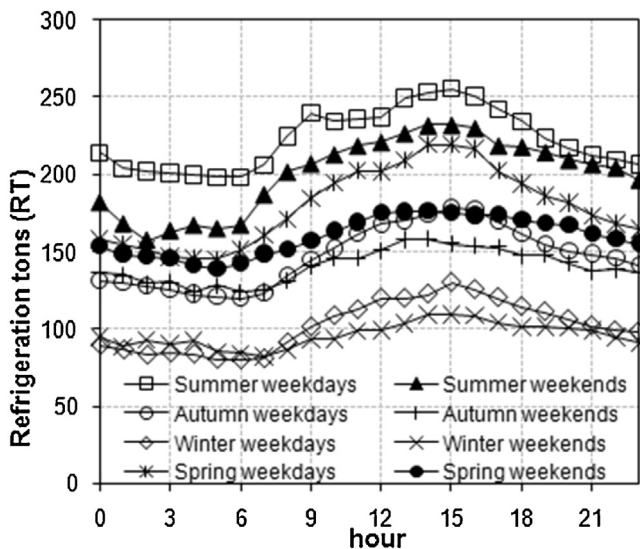


Fig. 5. Hospital cooling load (RT).

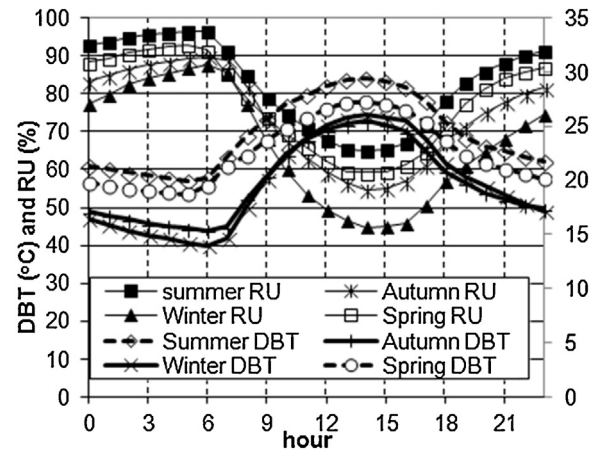


Fig. 6. Site climatic data.

The daily power to heat ratio (DPHR) of the hospital can be obtained dividing line 1 of Table 2 by the sum of lines 2 and 3. The DPHR of the hospital is calculated between 1.6 (winter weekends) and 2.3 (spring weekdays). The results are influenced by variations in the electricity consumption (mainly due to air conditioning) and steam consumption (depends on the hospital activity). Hot water energy consumption is small compared to steam (Table 2).

3. Methodology

The simulation is developed by software (COGMCI) consisting of Fortran engineering programs and a Delphi interface. Graphical results are generated by a spreadsheet that imports data from results files. The Fortran program is composed of one main algorithm and more than 20 subroutines dealing with (i) seven different engines, (ii) water and steam properties, (iii) exhaust gas properties, (iv) absorption chiller selection, (v) absorption chiller simulation, (vi) HRSG simulation, (vii) economizer design, (viii) economizer simulation, (ix) exhaust gas heat exchanger (EGHE) design, (x) EGHE simulation, (xi) exergy efficiency, (xii) heat exchanger design, (xiii) and heat exchanger simulation, among others.

The main program controls data entry, results and all of the calculations. The calculation procedures use polynomial curve fitting (engine and absorption chiller performance), deterministic modeling or mathematical representations of physical phenomena (heat transfer and pressure drops) and physical properties (water and exhaust gases). A computational algorithm involving several iterative procedures was developed, constituting an ITS, i.e., considering all of the pieces of equipment as a single system. This algorithm produces results as a function of demands, energy supplied by the engine, design parameters, equipment performance, and simplified hypothesis. The hourly profile simulation analysis approximates the dynamic nature of energy consumption in buildings and the dynamics of thermal equipment performance in an integrated system by a series of quasi-steady-state operating conditions with one-hour time-steps, as used by Lebrun [29].

The software can be used to design and simulate cogeneration and trigeneration systems attending energy demand profiles. The software use can be divided in five main steps:

- (1) Definition of the hourly energy profiles (electricity, steam, hot water, and chilled water).
- (2) Cogeneration or trigeneration system configuration should be defined (for example recovering engine exhaust gases energy in a HRSG for steam production, engine jacket water energy in an absorption chiller for chilled water production and engine

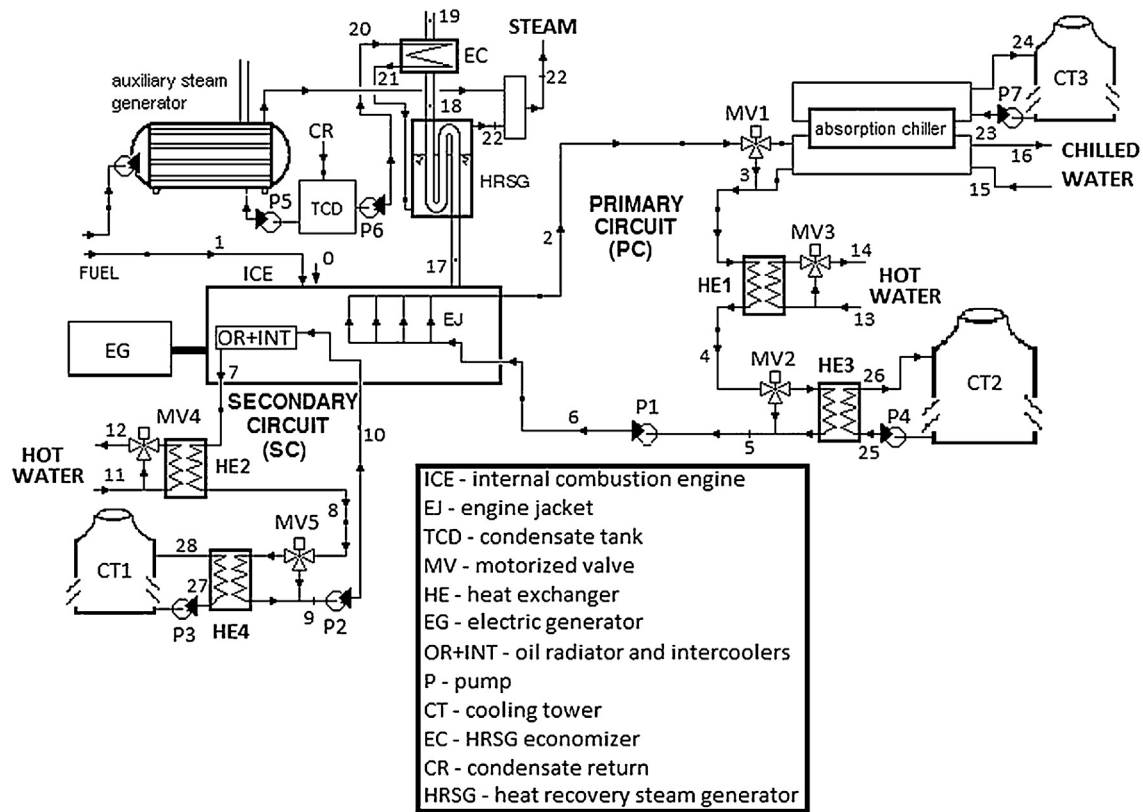


Fig. 7. Trigeneration scheme.

oil radiator and intercooler energy in a heat exchanger for hot water production). Up to 15 cogeneration and trigeneration configurations are available while others configurations are being developed.

- (3) The engine model to be simulated and some engine operational parameters (primary and secondary hot water temperatures, operational strategy: electrical dispatch or full load, etc.) should be defined.
- (4) Definition of energy recovery equipment design and/or selection parameters (HRSG, heat exchangers, absorption chiller, etc.).
- (5) Execution of the program. The defined system is simulated to attend the defined energy demand profiles.

Energy demand profiles are stored in a database, so different configurations, engine sizes and design parameters can be simulated.

The software can be used to optimize the energy savings, the payback period or other criteria defined by the user.

The software was previously utilized in others studies [2,30,31].

In this case study, the software is executed eight times to predict the performance of the trigeneration system on weekdays and weekends for the different seasons of the year.

4. Trigeneration system

Fig. 7 shows the trigeneration configuration evaluated herein. The flows are identified in the text by brackets. Table 3 shows the mass flow rate, temperature, pressure, enthalpy and entropy of the thermodynamic states in Fig. 7. Certain thermodynamic states were defined as input data, while the COGMCI software calculated others. The properties were obtained using the software EES (engineering equation solver).

The trigeneration system is formed by one internal combustion engine, primary and secondary hot water circuits, one HRSG with an economizer, one hot water single stage absorption chiller, and auxiliary equipment (pumps, cooling towers, heat exchangers, etc.).

The engine performance is based on a commercial engine [32] fueled by natural gas with an electric power of 1060 kW_e at the

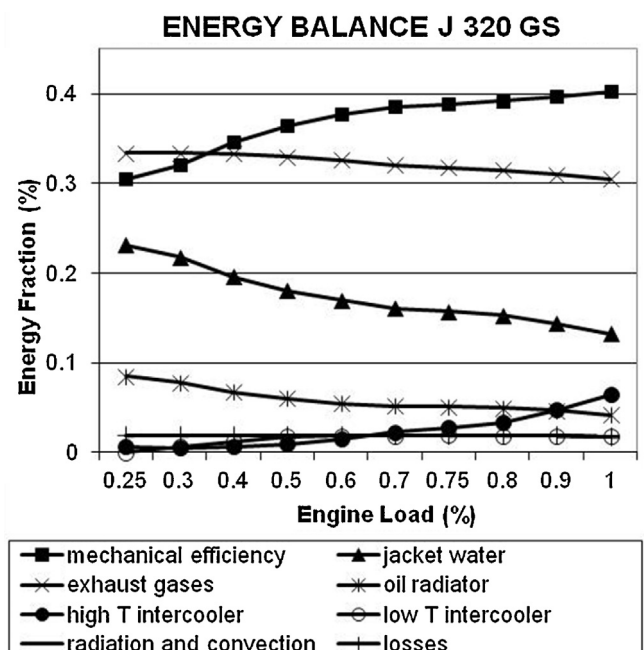


Fig. 8. Engine energy balance.

Table 3
Thermodynamic states of Fig. 7.

N	Fluid type	Flow rate (kg/s)	Temperature (°C)	Pressure (kPa)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)
0	air	1.5441	22.2	100	295.759	5.6897
1	fuel	0.0597673	22.2	100	45462	–
2	PC water	8.5554	90	475	377.248	1.1922
3	PC water	8.5554	80.53	425	337.449	1.0813
4	PC water	8.5554	79.97	325	335.032	1.0748
5	PC water	8.5554	79.97	325	335.032	1.0748
6	PC water	8.5554	80	550	335.326	1.075
7	SC water	4.0352	55	250	230.438	0.7678
8	SC water	4.0352	34.98	150	146.615	0.5046
9	SC water	4.0352	34.98	150	146.615	0.5046
10	SC water	4.0352	35	400	146.942	0.5048
11	Hot water	3.0896	22.2	310	93.326	0.3274
12	Hot water	3.0896	48.39	260	202.803	0.6827
13	Hot water	3.0896	48.39	260	202.803	0.6827
14	Hot water	3.0896	50	210	209.498	0.7036
15	Chilled water	10.5186	12.7	300	53.58	0.1907
16	Chilled water	10.5186	7.2	250	30.5	0.1093
17	Exhaust gases	1.6039	487	100	545.449	1.0988
18	Exhaust gases	1.6039	174.5	100	171.245	0.467
19	Exhaust gases	1.6039	115.9	100	104.578	0.3073
20	HRSG feed water	0.2847	70	900	293.72	0.9544
21	HRSG water	0.2847	160	800	675.757	1.9427
22	Steam	0.279	170.4	800	2768.892	6.6625

full engine load at 1800 rpm. Fig. 8 shows the engine energy balance and Fig. 9 shows the exhaust gas flow and temperature as a function of the engine load. The maximum engine mechanical efficiency (40.3%) is found at the full engine load; at this condition, 39% of the engine energy rate is converted into electricity. Correction for atmospheric pressure was not applicable in this study. Correction for dry bulb temperature assumes 0.5% loss of power for each degree Celsius above 25 °C. The ambient temperature does not affect the engine energy balance.

Electrical efficiency is defined as the engine mechanical efficiency multiplied by the electrical generator efficiency. Fig. 10 shows the electrical generator efficiency curve as a function of the engine load utilized in this study and the electrical generator efficiency part load curve reproduced from Haglind et al. [33].

The secondary circuit recovers energy from the engine oil radiator and intercoolers and then uses this energy to warm sanitation water at HE2. The primary circuit recovers energy from the engine jacket and uses this energy in the absorption chiller for chilled water production. If there is energy excess in the primary circuit water, this energy can be used to warm sanitation water at HE1 (after recovery at the secondary circuit). The energy from the

exhaust gases is used for steam generation in a HRSG with an economizer.

Design temperatures of hot water at the primary and secondary circuits are typical values utilized in engines. At the design condition, secondary circuit hot water enters the engine [flow 10] at 35 °C (fixed) and leaves it [flow 7] at 55 °C, while primary circuit hot water enters the engine [flow 6] at 80 °C and leaves it [flow 2] at 90 °C. Water flows at primary and secondary circuits are designed taking into account the energy rate and the design temperature difference (constant flow).

Heat exchangers HE1 and HE2, which recover energy from the primary and secondary circuits (sanitary hot water at 50 °C), are designed and simulated using the NTU (number of thermal units) method. The sanitary hot water flow is 7000 kg/h in the design for both heat exchangers. HE2 is designed assuming water entering at 22.2 °C and leaving at 50 °C, and HE1 is designed to receive sanitary hot water at 30 °C and to warm it to 50 °C (design condition). The inlet and outlet pressures in the two heat exchangers are 310 and 210 kPa (a step of 50 kPa in each). The sanitary hot-water recovers energy from HE2 [flows 11 and 12] and HE1 [flows 13 and 14] connected in series (cascaded) and the energy demands vary according

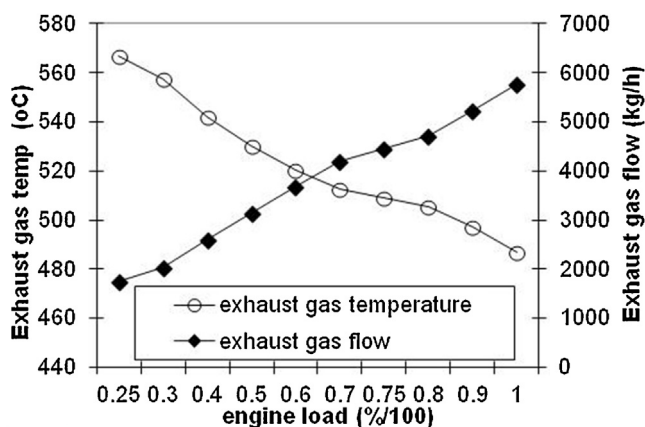


Fig. 9. Engine exhaust gas flow and temperature.

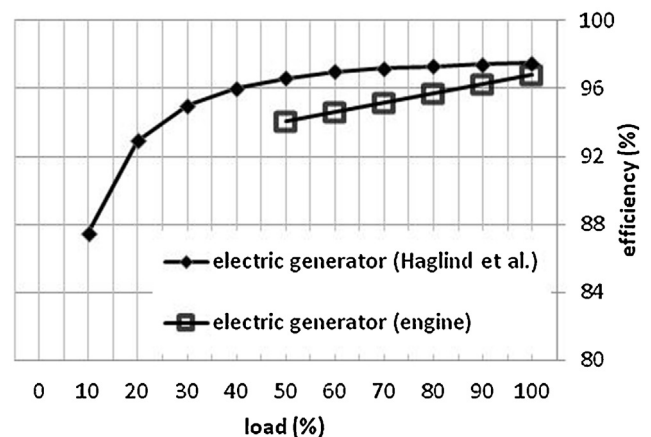


Fig. 10. Generator efficiency versus load.

to Fig. 3a and b. The energy balance on Table 3 does not represent the design conditions of heat exchangers (HE1 and HE2) because (i) the engine can operate at a partial load (lower primary and secondary circuit hot water temperature), (ii) hot water demand can be higher than the HE1 and HE2 design hot water flow (7 m³/h) and (iii) the absorption chiller can operate at a partial load (lower primary circuit hot water temperature difference ($T_2 - T_3$)). Under one of these conditions or a combination of them, oversized HE1 and HE2 can contribute to recovering more energy from the primary and secondary circuits.

The main parameters of the HRSG and its economizer are defined based on the methodology proposed by Ganapathy [34]. Saturated steam is produced at 8 bar (800 kPa) [flow 22], and the defined HRSG physical characteristics are the following: 350 tubes with diameters of 25.4/37.8 mm (internal/external) and 6.1 meters long. Heat loss of 2% and blow down of 2% are also adopted. The composition of the exhaust gases is assumed to be constant, with the properties evaluated at a mean temperature for both the HRSG and HRSG economizer. The make-up water [flow 20] leaves the condensate tank at 70 °C (constant), and HRSG feed water [flow 21] is designed to achieve a 10 °C approach point at the HRSG economizer with a heat loss of 2% assumed at this last component.

The absorption chiller (AC) selection and simulation are based on manufacturer performance curves [35]. The selected AC has a nominal capacity of 174 tons (610 kW) based on saturated steam at 184 kPa as the heat source, chilled water being produced at 7.2 °C (5.5 °C temperature difference) and water entering the condenser at 29.4 °C. The performance data for the AC follows the test procedure stipulated by ARI [36]. The program selects the AC based on the primary circuit water flow and temperature difference. In this study, hot water is assumed to enter the AC generator at 90 °C and leave at 80.5 °C; chilled and condensed water temperatures were defined at the nominal capacity condition (these represent the design condition of the chilled water plant at the hospital). The water flow at the condenser and absorber are operated as required by the manufacturer. The selected AC has a COP of 0.71. The AC avoids electricity demand at the electrical chillers by a rate of 0.8 kW/RT (COP equal to 4.4). Methodologies for predicting electrical chiller performance can be seen in Yu and Chan [37] and Espirito Santo [38].

Cooling towers and auxiliary heat exchangers are responsible for rejecting unused energy, preventing the engine from operating under unsafe conditions. This equipment will not be simulated, i.e., it is assumed that they can reject the energy as needed.

The total produced electricity is 3% higher than the net engine power, taking into account the use of electricity in auxiliary equipment, such as pumps, cooling towers, etc. (parasitic load). No heat loss is assumed at the exhaust gas ducts and hot water pipes.

As the revenue value for exceeding electricity transferred to the grid in Brazil is very low compared with the natural gas price, the engine is assumed to operate at electrical dispatch (following the electricity demand curve), and surplus electricity is imported from the grid as necessary.

5. Energy and exergy efficiency

EUF is defined as the sum of the trigeneration products energy rate divided by the engine energy input rate (Eq. (1)). The trigeneration products are the following: (i) net electricity, (ii) steam, (iii) hot water and (iv) chilled water. The energy rates of the steam, hot water and chilled water were calculated as the mass flow rates multiplied by the enthalpy differences, as shown in Eq. (2). The net power of the system is the engine full load power output less the parasitic load. The engine full load EUF is calculated as 85.4%; this value means that all of the trigeneration products are being utilized (demanded by the hospital). Fig. 11 shows the contribution of each

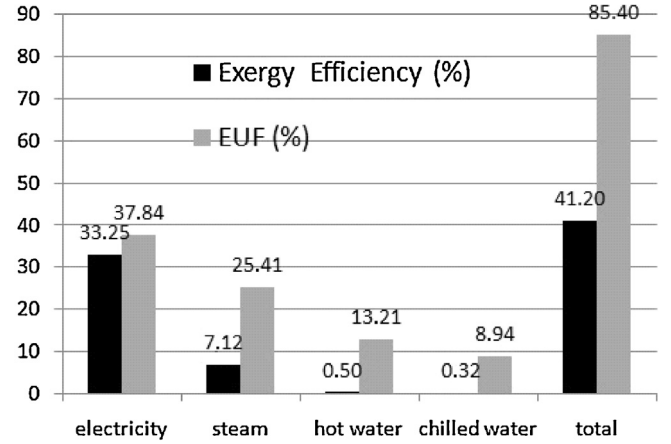


Fig. 11. Utilities participation on EUF and exergy efficiency.

utility to the final EUF. This figure shows that net electricity contributes 37.84%, steam contributes 25.41%, hot water contributes 13.21% and chilled water contributes 8.94%.

$$EUF = \frac{\dot{W}_{net} + \dot{E}_{steam} + \dot{E}_{ht} + \dot{E}_{cw}}{\dot{m}_{fuel} LHV_{fuel}} \quad (1)$$

$$EUF = \frac{\dot{W}_{net} + \dot{m}_{22}(h_{22} - h_{20}) + \dot{m}_{14}(h_{14} - h_{11}) + \dot{m}_{16}(h_{15} - h_{16})}{\dot{m}_1 \cdot LHV_{fuel}} \quad (2)$$

The exergy method is a thermodynamic analysis that takes into account the quality of the energy flows [39–42]. Exergy efficiency is defined as the total exergy rate of the trigeneration flows divided by the engine exergy consumption rate (Eq. (3)). The engine exergy consumption rate is calculated for the fuel standard chemical exergy (51,737 kJ/kg), assuming a natural gas composition of 90% CH₄, 8% C₂H₆ and 2% C₃H₈ [36]. The ambient reference is set to $T_0 = 22.2$ °C, and $P_0 = 100$ kPa.

$$\varepsilon = \frac{\dot{W}_{net} + \sum \dot{E}x_{flow}}{\dot{m}_{fuel} ech_{fuel}} = \frac{\dot{W}_{net} + \dot{E}x_{steam} + \dot{E}x_{ht} + \dot{E}x_{cw}}{\dot{m}_{fuel} ech_{fuel}} \quad (3)$$

The flow exergy can be calculated by:

$$\dot{E}x_{flow} = \dot{m}[(h_e - h_i) - T_0(s_e - s_i)] \quad (4)$$

Giving:

$$\dot{E}x_{steam} = \dot{m}_{22}[(h_{22} - h_{20}) - T_0(s_{22} - s_{20})] \quad (5)$$

$$\dot{E}x_{ht} = \dot{m}_{14}[(h_{14} - h_{13}) - T_0(s_{14} - s_{13}) + (h_{12} - h_{11}) - T_0(s_{12} - s_{11})] \quad (6)$$

$$\dot{E}x_{cw} = \dot{m}_{16}[(h_{15} - h_{16}) - T_0(s_{15} - s_{16})] \quad (7)$$

Fig. 11 shows that the contribution from the utilities to the exergy efficiency is 41.2%. Electricity, steam, hot water, and chilled water respectively contribute 33.25%, 7.12%, 0.5%, and 0.32% to the exergy efficiency.

6. Simulation results

6.1. Summer

The higher energy consumption of the hospital occurs in the summer, due to air conditioning usage and hospital activity (peak of electricity and steam consumption).

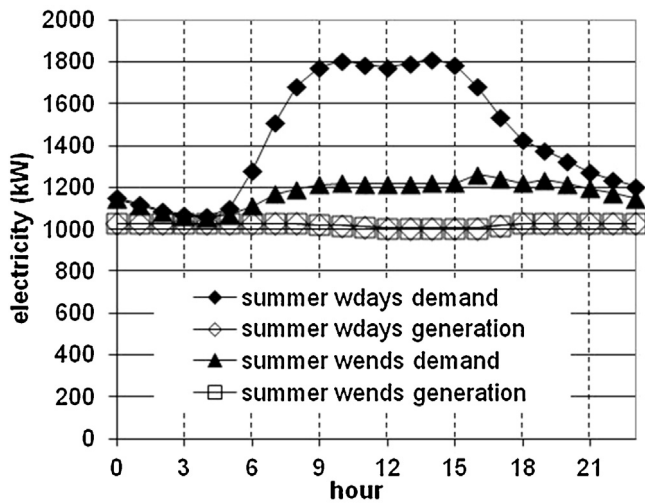


Fig. 12. Electricity in summer.

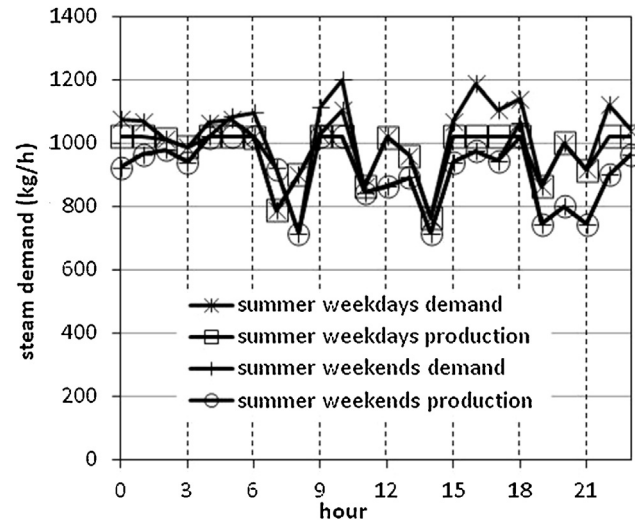


Fig. 14. Steam in summer.

Summer results for weekdays and weekends are shown in Figs. 12–15. Fig. 12 shows the predicted electricity demand (this electricity demand considers the electricity for the electrical chillers that is substituted by operating the absorption chiller). The engine is expected to operate at a full load at all times and the additional electricity must be purchased from the grid.

The AC production is calculated as 69 RT (242 kW), as shown in Fig. 13. The chiller capacity is constant given that the engine operates at the full load at all times and the temperature of the primary circuit water leaving the engine remains constant. The existing electrical chillers produce complementary chilled water.

The calculated steam production is 1015 kg/h when the engine operates at the full load (Fig. 14). When the steam demand is lower than 1015 kg/h, a fraction of the exhaust gases should be by-passed to adjust production to demand. When the steam demand is higher than 1015 kg/h, the complementary steam generator should operate.

In Fig. 15 the sanitary hot water demand and production can be compared. The engine secondary circuit has 339 kW (12.9% of engine energy rate) when the engine operates at the full load. It can be seen that the demand and production are coincident, indicating that the trigeneration system met the demand.

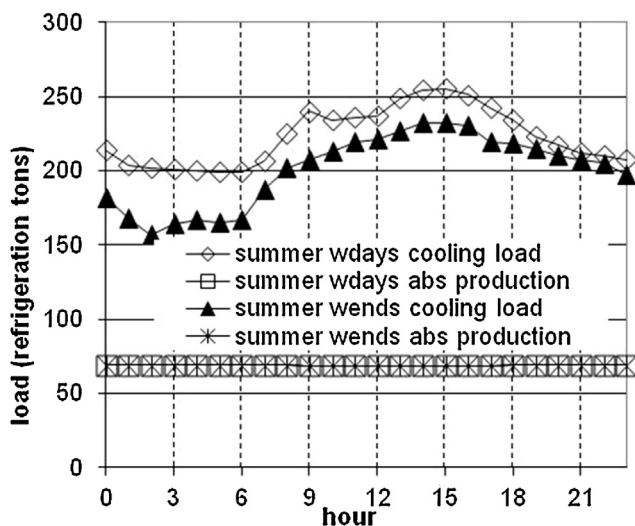


Fig. 13. Absorption chiller in summer.

6.2. Autumn

In the autumn the hospital's electricity consumption is reduced by approximately 20% when compared to the summer. The steam consumption is reduced in about 30% and the hot water consumption increases.

Autumn results for weekdays and weekends are shown in Figs. 16–19. Fig. 16 shows the predicted electricity demand (due to the AC operation). The electricity demand and production can be compared. The engine is expected to operate at a partial load between hours 0 to 6 and 22 to 23 on weekdays and between the hours of 0 and 8 and 19 and 23 on weekends. The engine operates at the full load, and additional electricity must be purchased from the grid for the remaining hours.

The AC production is calculated between 68 and 69 tons (238 and 242 kW), as shown in Fig. 17. The AC capacity is nearly constant even when the engine is operating at a partial load, given that the engine has more energy available from the jacket water (Fig. 8) and the temperature of the primary circuit water leaving the engine remains nearly constant. The cooling load is higher than the AC capacity, indicating that the existing electrical chillers should provide complementary capacity.

The trigeneration system is expected to meet the steam demand, except on weekdays at hour 23 (Fig. 18).

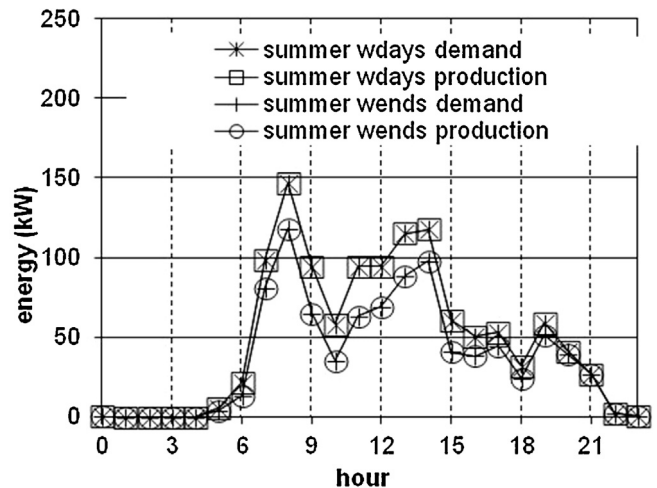


Fig. 15. Hot water in summer.

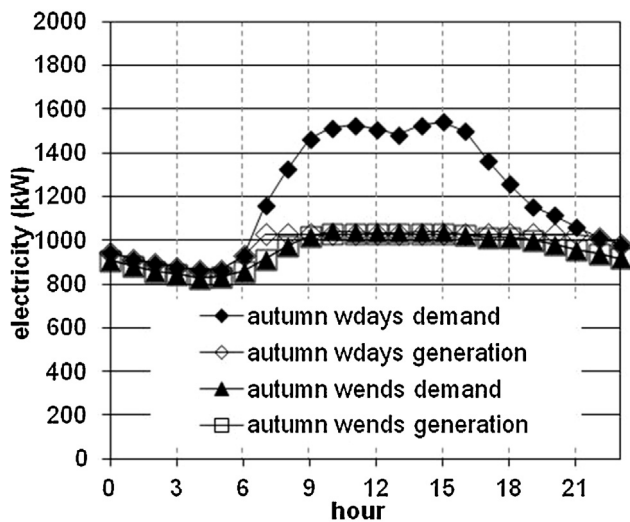


Fig. 16. Electricity in autumn.

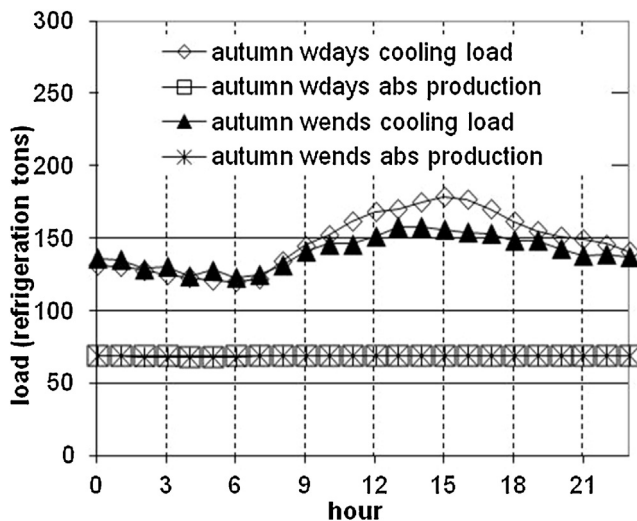


Fig. 17. Absorption chiller in autumn.

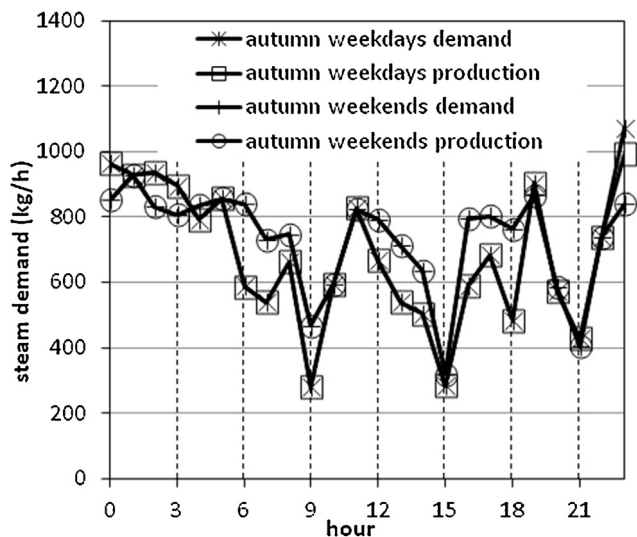


Fig. 18. Steam in autumn.

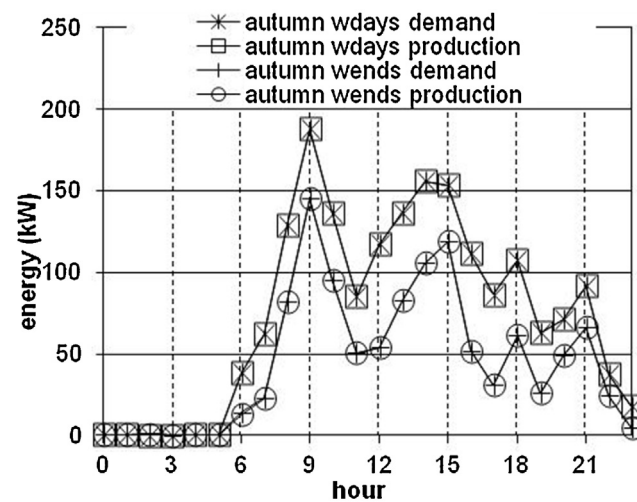


Fig. 19. Hot water in autumn.

In Fig. 19, the sanitary hot water demand and production can be compared. This figure shows that demand and production is coincident, meaning that the trigeneration system met the demand.

6.3. Winter

In the winter electricity consumption reaches its lower value while the steam consumption is close to the autumn's value. Sanitary use hot water demand is higher in the winter but it represents a small energy consumption of the hospital. Due to the weather temperatures in the winter few energy is consumed for heating (air conditioning).

Due to the tropical weather at the hospital location, a small amount of energy is used for space heating (air conditioning) in the winter.

Winter results for weekdays and weekends are shown in Figs. 20–23. Fig. 20 shows the predicted electricity demand (due to the AC operation). The electricity demand and production can be compared. The engine is expected to operate at a partial load between hours 0 to 6 and 21 to 23 at weekdays and during the entire day on weekends.

The AC production is calculated between 67 and 69 tons (234 and 242 kW), as shown in Fig. 21. Fig. 21 illustrates that AC

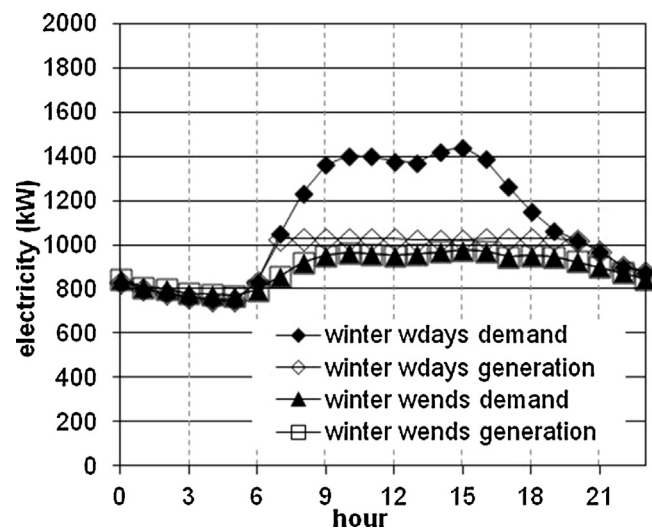


Fig. 20. Electricity in winter.

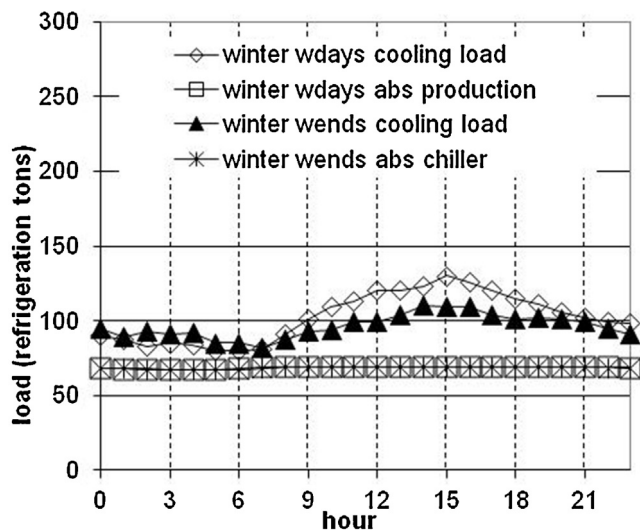


Fig. 21. Absorption chiller in winter.

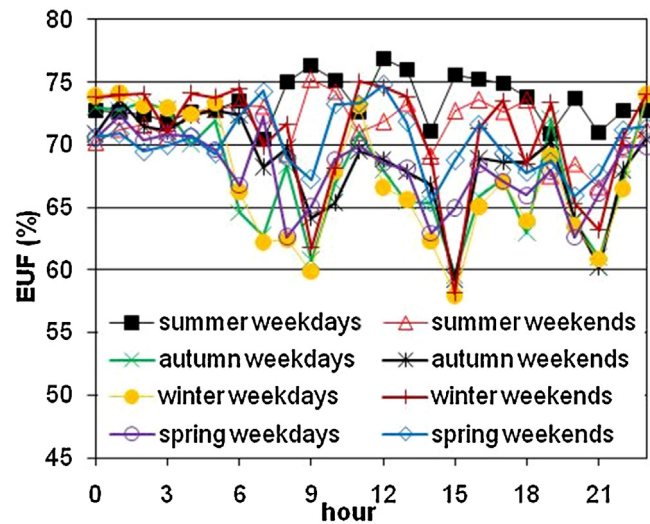


Fig. 24. Energy utilization factor.

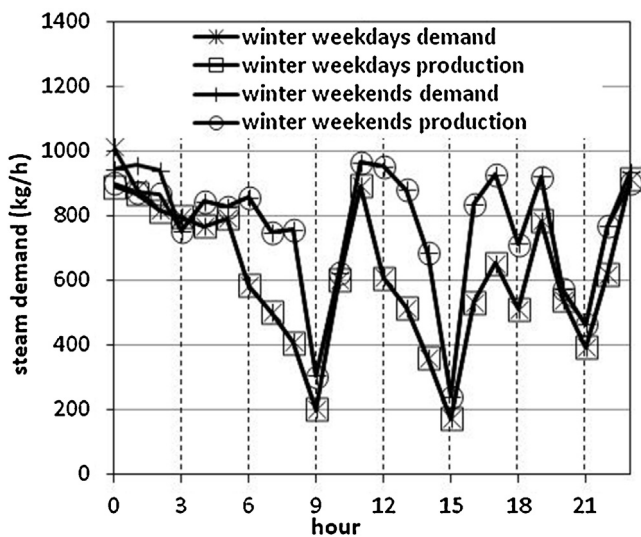


Fig. 22. Steam in winter.

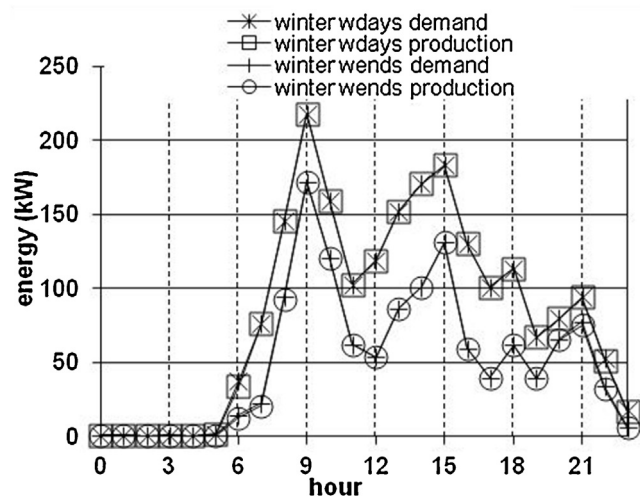


Fig. 23. Hot water in winter.

production nearly met the hospital cooling load. Existing electrical chillers should produce complementary chilled water.

The steam demand is not completely met between hours 0 and 1 on weekdays and 0 and 2 and 23 on weekends (Fig. 22). Production is adjusted for demand using the complementary steam generator and by-passing part of the exhaust gases.

In Fig. 23, the sanitary hot water demand and production can be compared. This figure shows that demand and production are coincident. During winter, the sanitary hot water demand reaches a peak value.

6.4. Spring

Since the spring energy demand and consumption is quite similar to autumn's ones, the figures are not shown. The engine is expected to operate at a partial load between the hours of 0 and 5 and 23 at weekdays and during the hours of 0 and 6 and 22 and 23 on weekends. For the remaining hours, the engine operates at the full load and additional electricity must be purchased from the grid.

The AC production is calculated between 68 and 69 tons (238 and 242 kW). The electrical chiller provides complementary chiller capacity to respond to changes in the hospital cooling load.

The steam demand and production are adjusted using complementary steam generator and by-passing part of the exhaust gases.

The sanitary hot water demand and production are coincident, meaning that the trigeneration system met the demand.

6.5. Energy utilization factor (EUF)

The EUF (Eq. (1)) results can be seen in Fig. 24.

In summer, the engine operates at the full engine load, and electricity contributes 37.8% to the EUF. The contribution of steam varies from 18.1% (hour 8 on the weekend) to 26.2% (hour 4 on weekdays). Sanitary hot water contributes 0 to 5.4% (hour 8 on weekdays) and chilled water contributes 8.9% (almost constant).

In autumn the engine operates at both a partial load and the full load. The electricity contribution to the EUF varies between 36.4% (hour 4 on weekends) and 37.8%. The contribution of steam varies from 7.1% (hour 9 on weekdays) to 26.4% (hour 1 on weekends). Sanitary hot water contributes 0 to 6.9% (hour 9 on weekdays), while chilled water contributes 8.9% (full engine load) to 10.5% (hour 4 on weekends—engine part load).

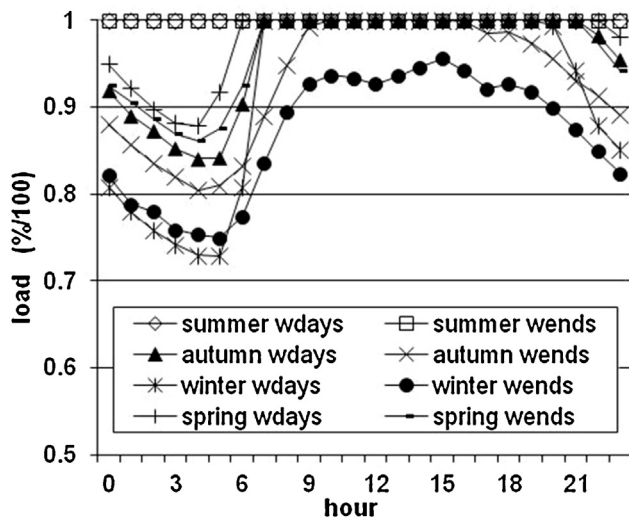


Fig. 25. Engine load factor.

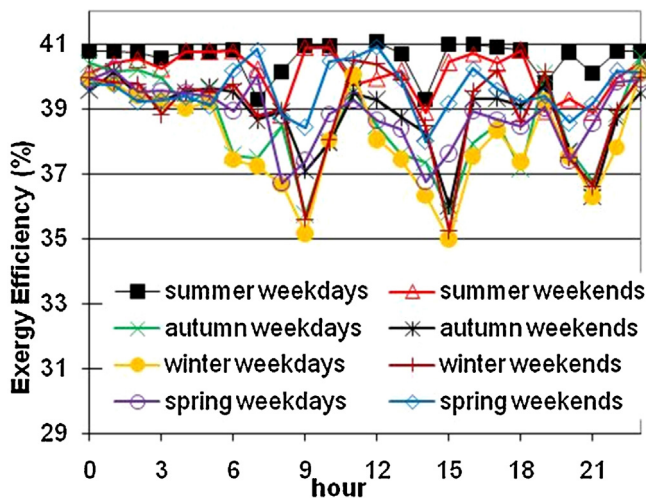


Fig. 26. Exergy efficiency.

In winter, the engine operates at partial load and at full load. The electricity contribution to the EUF varies between 35.8 (hour 5 on weekdays) to 37.8%. The contribution of steam varies from 4.4% (hour 15 on weekdays) to 26.9% (hour 4 on weekends). Sanitary hot water and chilled water respectively contribute 0 to 8% (hour 9 on weekdays), and 8.9% (engine full load) to 11.2% (hour 5 on weekdays).

In spring the engine operates at a partial load and the full load. Electricity contribution to the EUF varies between 36.8 (hour 4 on weekends) to 37.8%. The contribution of steam varies from 10.5% (hour 8 on weekdays) to 26% (hour 12 on weekends). Sanitary hot water and chilled water respectively contribute 0 to 5.4% (hour 9 on weekdays) and 8.9% (engine full load) to 10% (hour 4 on weekends).

A mean annual EUF of 69.3% is obtained (72.8% in summer, 67.8% in autumn, 68.2% in winter and 68.7% in spring). The mean engine load factor can be seen in Fig. 25. The lower engine load factor is close to 0.73, and a mean engine load of 0.96 is expected to occur in a one-year operation period.

6.6. Exergy efficiency

Exergy efficiency (Eq. (3)) results can be seen in Fig. 26.

In summer, the engine operates at full load all the time and electricity contributes 33.25% to the exergy efficiency. The contribution of steam varies from 5.1% (hour 8 on weekend) to 7.3% (hour 12 on weekdays). Sanitary hot water and chilled water respectively contribute 0–0.21% (hour 8 on weekdays) and 0.32% (almost constant).

In autumn, the engine operates at a partial load and the full load. The electricity contribution to the exergy efficiency varies between 32 (hour 4 on weekends) to 33.25%. The contribution of steam varies from 2% (hour 9 on weekdays) to 7.38% (hour 1 on weekends). Sanitary hot water and chilled water respectively contribute 0 to 0.28% (hour 9 on weekdays) and 0.32% (engine full load) to 0.37% (hour 4 on weekends—engine part load).

In winter, the engine operates at a partial load and the full load. The electricity contribution to the exergy efficiency varies between 31.4 (hour 5 on weekdays) to 33.25%. The contribution of steam varies from 1.2% (hour 15 on weekdays) to 7.5% (hour 4 on weekends). Sanitary hot water and chilled water respectively contribute 0–0.31% (hour 9 on weekdays) and 0.32% (engine full load) to 0.4% (hour 5 on weekdays).

In spring the engine operates at a partial load and the full load. The electricity contribution to the exergy efficiency varies between 32.3 (hour 4 on weekends) to 33.25%. The contribution of steam varies from 2.9% (hour 8 on weekdays) to 7.2% (hour 12 on weekends). Sanitary hot water and chilled water respectively contribute 0 to 0.21% (hour 9 on weekdays) and 0.32% (engine full load) to 0.36% (hour 4 on weekends).

Fig. 26 shows that the exergy efficiency varies between 35% and 41% and that a mean exergy efficiency of 40.4%, 38.6%, 38.3% and 39.1% was calculated for summer, autumn, winter and spring respectively. A mean annual value equal to 39.05% was calculated.

6.7. Primary energy savings (PES)—daily energy analysis

The trigeneration system simulation reveals that surplus electricity will be purchased from the grid, complementary steam will be produced at the existing steam generators, hot water demand will be completely met by the trigeneration system and complementary chilled water will be produced at the existing chiller.

Table 4 reveals the energy consumption of the hospital taking into account the implementation of the proposed trigeneration solution. At lines 1, 2 and 3, the daily complementary electricity, steam and hot water for each group of data, respectively, are shown. Line 4 shows the daily natural gas consumption of the engine obtained from the simulation analysis. Line 5 shows the trigeneration system electricity production. Using the production efficiencies of electricity (38%), steam (80%) and hot water (80%), the mean daily energy consumption of the hospital can be estimated (line 6 of Table 4). The daily primary energy consumption is multiplied by the number of days for each group of data to calculate the primary energy consumption for each group of data (line 7). The sum of the primary energy consumption results of the eight groups is the annual primary energy consumption of the hospital, estimated as 25,555,659 kWh/year. In Table 2 the annual energy consumption of the hospital is calculated as 34.8 GWh/year. The result shows that the implementation of the trigeneration system represents a PES of 26.6%.

7. Results and discussion

The steam and chiller water contributions to the EUF and to the exergy efficiency can be higher at a partial engine load than the full load, because more energy is available in the exhaust gases and at the primary circuit when the engine operates under a partial load (Fig. 8).

Table 4
Daily and annual energy consumption (with trigeneration).

With Trigeneration	Summer		Autumn		Winter		Spring	
	Weekdays	Weekends	Weekdays	Weekends	Weekdays	Weekends	Weekdays	Weekends
Electricity consumption—grid (kWh/day)	10121.1	3690.1	5088.9	54.0	3574.4	0.0	6318.1	1016.8
Steam consumption—surplus (kWh/day)	629.6	338.3	64.8	7.5	105.1	179.4	2.3	7.0
Hot water consumption—surplus (kWh/day)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural gas consumption (kWh/day)	59545.7	59545.7	57963.6	56377.0	55686.0	53344.7	58591.0	58045.5
Electricity production (kWh/day)	25290.4	25290.4	24440.3	23639.3	23323.7	22104.3	24778.7	24501.4
Daily energy consumption (kWh/day)	86967.1	69679.3	71436.5	56528.5	65223.8	53569.0	75220.5	60730.1
Annual consumption (kWh/year)	5218026.0	2020699.8	4643373.4	1582796.9	4369997.4	1446361.8	4513232.2	1761171.8
Annual total consumption (kWh/year)	25555659.28							

Table 5
Daily and annual energy consumption (with and without trigeneration)—10% loss in the electrical grid.

Without Trigeneration	Summer		Autumn		Winter		Spring	
	Weekdays	Weekends	Weekdays	Weekends	Weekdays	Weekends	Weekdays	Weekends
Electricity consumption (kWh/day)	39970.0	32824.4	33473.3	27022.2	30578.9	25306.7	35202.2	29014.4
Steam consumption (kWh/day)	16609.3	15356.0	11227.7	12079.7	10205.2	12648.7	11978.0	13896.5
Hot water consumption (kWh/day)	1174.3	903.5	1791.7	1088.0	2024.5	1244.2	1483.4	844.0
Daily energy consumption (kWh/day)	80157.0	67896.0	64786.3	55622.3	59604.4	54042.4	67844.5	60475.5
Annual consumption (kWh/year)	4809419.4	1968983.3	4211111.2	1557425.3	3993495.7	1459143.9	4070669.1	1753790.2
Annual total consumption (kWh/day)	23824038.1							
With Trigeneration								
Electricity consumption—grid (kWh/day)	11245.6	4100.1	5654.3	60.0	3971.6	0.0	7020.1	1129.8
Steam consumption—surplus (kWh/day)	629.6	338.3	64.8	7.5	105.1	179.4	2.3	7.0
Hot water consumption—surplus (kWh/day)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural gas consumption (kWh/day)	59545.7	59545.7	57963.6	56377.0	55686.0	53344.7	58591.0	58045.5
Electricity production (kWh/day)	25290.4	25290.4	24440.3	23639.3	23323.7	22104.3	24778.7	24501.4
Daily energy consumption (kWh/day)	76630.7	65910.7	66239.3	56473.4	61573.4	53569.0	68768.0	59691.6
Annual consumption (kWh/year)	4597844.2	1911411.6	4305557.6	1581253.8	4125415.3	1446361.8	4126080.4	1731057.2
Annual total consumption (kWh/year)	23824981.9							

An annual mean EUF equal to 69.3% is calculated. A maximum EUF value is calculated as 76.8% (summer weekdays at hour 12). The obtained results are in agreement with the results obtained by other authors that evaluated engine trigeneration systems [8,43]. In Section 5, the EUF was calculated as 85.2% using EES. The EUF simulation results can be compared with the EUF calculated using the software EES when the following criteria are met: (i) the engine operates at the full load; (ii) all the trigeneration products are demanded by the hospital; and (iii) the absorption chiller, HRSG with economizer and the heat exchangers are simulated at the conditions in Table 3. The maximum EUF is never obtained in the simulation analysis, mainly because the hot water demand has a maximum value of 6800 kg/h (1.9 kg/s), as shown in Fig. 3b, while the EUF calculated using EES takes into account a hot water production of 11100 kg/h (3.09 kg/s)—(Table 3). Partial load engine operation, power corrections due to high ambient temperatures and no coincidence of high demand of steam and sanitary hot water also contributed to the lower EUF obtained by the simulation.

Exergy efficiency analysis takes into account the energy quality and is therefore more effective than the EUF when comparing solutions. The mean annual exergy efficiency is calculated as 39.05%, and the maximum value is 41.05% (summer weekdays hour 12), in agreement with results of cogeneration exergy studies developed by other authors [8,44,45]. As exergy analysis represents a quantification of energy quality, the exergy efficiency is much lower than the EUF. Electricity and steam have the greatest impact on the exergy efficiency. The contribution of hot water and chilled water to the exergy efficiency is small (below 1%), because the defined temperature and pressure of the hot water and chilled water flows are close to the ambient reference condition (T_0, P_0). For this reason, the exergy efficiency is also small for direct-fired hot water boilers and in electrical chillers. Therefore, despite the low contribution to the exergy efficiency, the production of hot and chilled water from residual engine energy is a good design choice. A comparison

between exergy efficiency values calculated by the simulation and by the EES software can be performed when the following criteria are met: (i) the engine operates at full load; (ii) the by-product quantities are similar to those in Table 3; and (iii) the absorption chiller, HRSG with economizer and the heat exchangers are simulated at the conditions in Table 3. The exergy efficiency calculated using the EES software (Section 5) was not obtained by the simulations due to variations in the hot water and steam demand, the partial load engine operation and the engine power correction at high ambient temperatures.

Simulating the trigeneration system with the software COGMCI at the conditions in Table 3 result in a EUF equal to 85.52% (electricity, steam, hot water and chilled water respectively contribute 37.84%, 25.57%, 13.2%, and 8.92%) and an exergy efficiency of 41.21% (electricity, steam, hot water and chilled water respectively contribute 33.25%, 7.14%, 0.504%, and 0.319%).

The PES analysis uses the first law of thermodynamics and energy efficiency conversion to quantify the primary energy consumption, allowing for effective solution comparisons. A PES of 26.6% is obtained when comparing the proposed trigeneration solution with the actual situation.

Utilizing the data in Tables 2 and 4, the proposed trigeneration solution is estimated as competitive with centralized electricity production with a thermal efficiency as high as 62.1%. Utilizing this value as the thermal efficiency of the centralized electricity production in Tables 2 and 4 and calculating the hospital annual primary energy consumption results in similar values of primary energy consumption in both tables (the PES of the trigeneration solution is zero).

Old transmission lines, transformers and circuit breakers are responsible for high losses in electricity transmission. Lera and Ballester [46] estimated that the electricity transmission loss could be as high as 20%. Taking into account a 10% loss in the electrical grid, the primary energy consumption of the hospital can be

recalculated as 37,974,386 kWh/year (line 1 of Table 2 is divided by 0.9, and the annual primary energy consumption is recalculated). Utilizing 69% as the thermal efficiency of centralized electricity production in Tables 2 and 4 (line 1 of Table 4 is also divided by 0.9), results in similar values for the primary energy consumption in both tables (PES of the trigeneration solution is zero); see Table 5. Taking into account a grid loss of 20%, the trigeneration system can be as good as a centralized electricity production plant with 77% thermal efficiency.

8. Conclusions

A detailed simulation methodology was developed to predict the performance of a proposed trigeneration system using COGMCI software. The simulation results are in good agreement with the results obtained using EES software and with the results obtained by other authors.

Energy demands of a hospital were obtained through a data acquisition system. A detailed analysis of the hospital energy consumption data, including a statistical treatment of the data and load duration curves is being planned to be presented in a future study. More complex data acquisition systems that evaluate the efficiency of the existing equipment (boiler, steam generator and electrical chillers) can be implemented to allow for a better analysis of the site energy consumption.

Energy policymakers can use PES analysis to compare the performance of trigeneration systems with centralized electricity thermal plants [47]. The results conclude that the proposed trigeneration solution can be competitive with a centralized thermal plant with over 62% (neglecting electricity transmission losses) or 77% (assuming a 20% electricity transmission losses) thermal efficiency.

Computational programs are reducing energy consumption in new and existing buildings [27–48]. These software programs mathematically predict the energy consumption of buildings to represent physical phenomena. Some energy (sanitary hot water, process steam, etc.) and electrical demands (lights, internal equipment, etc.) can only be predicted under the following circumstances: (i) typical energy consumptions (in W/m², for example) and (ii) assumed hourly profiles of use. These simulation programs allow for the comparison of improvements in the building structure and equipment (lights, internal equipment, HVAC systems, etc.). The comparisons are not so affected by the assumed typical energy consumption and profiles because the same assumptions are used in all of the cases being compared, but to sizing the trigeneration systems to real energy demands can lead to better solutions.

The proposed methodology can contribute to trigeneration systems that are able to operate with high efficiency for several different annual energy profiles found in typical buildings. This system can reduce the energy consumption of existing low-efficiency and high-efficiency buildings (designed for low energy consumption). Different buildings types can be further investigated.

The challenge of more sustainable global resource utilization requires the technical identification and development of solutions with lower environmental impact. High-efficiency trigeneration systems generally require a higher investment during the development phase and when constructing the system. International and local governmental incentives to implement high-efficiency systems must be developed.

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